THE SCIENTIFIC MONTHLY

FEBRUARY, 1921

HISTORY OF GEOLOGY*

By Professor HERBERT E. GREGORY
YALE UNIVERSITY

Introduction

THE history of geology is essentially the history of the intelligent observation of rocks, fossils and land forms. Progress is marked by progressive increase in exactness and completeness of observation. In an atmosphere saturated with tradition and personal bias the making of observations and the interpretation of observations present but a sickly growth; and when the intellectual environment includes authority and a complete outfit of supernatural causes, growth is stopped entirely. This may in part account for the interesting fact that philosophy and literature rather than observational science represent the intellectual efforts of the ancients. Poetry and musings about the nature of things require no special technique, no collections of materials for comparison. A gifted mind is the essential equipment; and such minds may appear anywhere and at any time. But the development of natural science involves critical observation of a variety of things from many places, the interchange of ideas among many workers, the making of hypotheses, the formulation and selection of method, and the invention of apparatus. It is natural that this group of requirements should come together slowly.

In no real sense can the obvious geological truths irregularly interwoven in the interesting fabric of myth and fact which constitutes Greek, Arabic, Indian, and Chinese thoughts on Nature be considered the beginnings of geology. The traditions of the Mediterranean peoples, of the Hebrews, Babylonians, and Hindus, are rich in speculation and in the making of hypotheses regarding earth origin, but poor in logical deduction from exact observation. They show little interest in the earth itself and no inkling that the history of the earth is to be deciphered by means of fossils, knowledge of the earth's crust, and the action of rivers and waves. The test is the extent to which

*Lecture delivered at Yale University, November 18, 1920, in a series on the History of Science under the auspices of the Yale Chapter of the Gamma Alpha Graduate Scientific Fraternity.

the contributions of the ancients were utilized as stepping stones. In geology progress has been attained without regard to or even in ignorance of observation and theories recorded before the late Middle Ages. Cuvier established paleontology without reference to the teachings of previous times and even in ignorance of the work of his contemporaries, and Darwin acknowledged his indebtedness to Lamarck, not to Aristotle, whose theory of evolution lacked little of being complete. Likewise structural geology, stratigraphy, and physiography have grown up without assistance from classical and Middle Age scholars. The fifteenth century student of earth science enjoyed a surprisingly meager heritage from classical and early Christian days. In the sixteenth century Leonardo da Vinci stands alone. During the seventeenth century many sciences made great strides forward; new facts were unearthed and methods established. Physics received the contributions of Galileo, Kepler, Newton, Torricelli, Guericke, Boyle, Huygens, Hooke. Astronomy, already far advanced, was revolutionized by the development of the telescope, and biology by the microscope. Chemistry found a place apart from alchemy and medicine. In geology, on the other hand, the seventeenth century scholar was groping in darkness scarcely less dense than that surrounding his predecessors of the sixteenth and fifteenth centuries.

Toward the close of the eighteenth century many of the facts and principles and methods which constitute geology were assembled but geology as taught today is essentially a nineteenth century product to which many of the most significant contributions have been made by scholars of the present generation.

The subject matter of geology is so varied and the introduction of new views so irregularly placed in time, that no chronologic sequence appears in the growth of the science as a whole. Development may best be shown by tracing the growth of certain fundamental ideas: the origin of the earth; the meaning of rocks, mountains, surface features and fossils; and the geologic time scale.

Origin of the Earth

From direct observation geology knows nothing of the original earth; no part of its first formed surface has been seen or is likely ever to be seen. The oldest rocks known have doubtless been derived from rocks yet older, and the oldest fossil undoubtedly descended from a long line of still older organisms. The evolution of the physical earth and of life clearly point to a period charged with dynamic and vital forces long antedating the most ancient legible records.

It must be admitted that so far little clear light has been thrown on the origin and primeval condition of the earth. For the geologist

there is little choice between the childlike myths of the Eskimos, Bushmen, and Micronesians, the grand poetic conceptions of the Hindus, Babylonians, and Hebrews, and the pseudoscientific teachings of the Greeks and medieval churchmen.

An advance is recorded during the seventeenth century in the contributions of Descartes (1596-1650) and Leibnitz (1646-1716) who traced the development of the earth from a disordered mass of glowing material to a smooth, solid globe, the exterior of which had cooled. These ideas were expanded and built into a consistent theory through the labors of Kant (1755) and especially of Laplace (1796)[1], whose views of earth origin received well-nigh universal acceptance during the nineteenth century. In essence the nebular hypothesis of Laplace assumes the existence of highly heated gaseous nebulae slowly rotating about a central mass which eventually became the sun. As this nebulous material rotated, cooled, and contracted, rings of matter were detached one after another furnishing the stuff for planets and satellites. One of these rings, gathered into a spheroid, became the earth. The original earth, therefore, was a luminous star surrounded with a heavy vaporous atmosphere. The ball passed from a gaseous to a liquid state and developed a wrinkled crust of igneous rock like granite. Later the atmosphere gave rise to oceans and streams, agents for the production of sedimentary rock.

The nebular hypothesis is the crowning achievement in cosmical geology up to the end of the nineteenth century, but its value lies not so much in its inherent probability as in the absence of a better theory. It violates the principles of thermo-dynamics and of celestial mechanics and is out of accord with the present knowledge of nebulae, planets and satellites. Furthermore, the theory demands progressive cooling of the earth, and an arrangement of rock masses amply disproved by geological evidence. Without radical reconstruction, the nebular hypothesis can no longer serve as a reasonable theory of earth origin.

The underlying conceptions of the nebular hypothesis are: first, the condensation of diffuse matter under the action of gravity, and second, nebulae distended by heat and revolving as a unit mass. But the researches in astronomy and physics during the past quarter century have accumulated evidence to show that disruption and repulsion, not attraction, are the dominant forces in the stellar universe. The tails of comets turned away from the sun, streamers thrown from the sun itself, and the shape of certain star clusters and nebulae point to prodigious repelling forces within the luminous bodies making up the universe. On such evidence the planetesimal hypothesis of Chamberlin and Moulton is founded.[2] Under this theory the earth was once

[1]Laplace, P. S., Exposition du système du monde, Paris, 1796 and 1824.
[2]Chamberlin, T. C., The origin of the earth, University of Chicago Press, 1916.

a spiral nebula composed of matter "thrown out" by some ancestral sun. The scattered particles, or planetesimals, of the parent nebula were drawn into nuclei which became part of the planetary system. At this stage the cosmic history of the earth passes into the geological history. The original earth is conceived as a ball 2,000 to 3,000 miles in diameter, which grew to its present size by the addition of more planetesimals. The heat of the earth comes from self-condensation and progressive close-packing of its constituent planetesimals. Under this theory vulcanism was active long before the earth attained its present size, and an atmosphere appeared as soon as the earth possessed sufficient gravitative power to retain it. When the atmosphere became saturated with aqueous vapor, water was formed and occupied depressions in the earth's uneven surface.

The truth of the planetesimal hypothesis remains to be separated from its errors by a long period of testing and developing. Its value lies in the fact that it explains a great number of geological observations and suggests lines for future investigation.

Meaning of Rocks

The origin of the earth and the history of life on this planet are involved in religious and philosophic views and therefore precede in point of time the study of the materials of which the earth is composed. At the beginning of the nineteenth century some progress had been made in the knowledge of minerals[3] but so little was known of the composition and texture of rocks that masses of igneous origin were confused with strata laid down by water or by wind, and the existence of vast exposures of metamorphic rocks was not recognized. The distinction between a rock and a geological formation or group of strata had not been fully established, and many fine-grained rocks were classed as minerals. As late as 1837 the Munich chemist, Johann Fuchs, contended strenuously for the view that mica schist, granite, and porphyry were the results of the consolidation of a watery paste. Only within the past fifty years has the systematic investigation of rocks—their composition, relations and origins—reached a stage that justified the recognition of a distinct branch of geologic science. Since the importance of its contributions has been demonstrated, the study of rocks has experienced two somewhat distinct but logical periods of development. *Petrography*, the description of rocks, is a necessary forerunner to *Petrology*, researches in the origin and broader relations of rocks.[4]

[3]Ford, W. E., The growth of mineralogy from 1818 to 1918: A century of science in America, pp. 268-283, Yale University Press, 1918.

[4]Pirsson, L. V., The rise of petrology as a science: A century of science in America, pp. 248-267, Yale University Press, 1918.

Cross, Whitman, The development of systematic petrography in the nineteenth century: *Jour. Geology,* X, 332-376, 451-499, 1902.

The stages of advancement in petrography may be traced by noting the systems of classifications in vogue at different periods, for classification involves the application of all known facts about all known kinds of rocks and also a consideration of existing theories and assumptions. The classifications of rocks based on hardness, specific gravity, and geographical location, are obviously superficial and one may dismiss as a humorous but futile notion the dictum of Jameson that there is but one species in mineralogy, namely, the globe, and the wordy argument of Pinkerton (1811) that no *species* of minerals exist for no mineral has the capacity to reproduce its kind. It is easy to understand, however, that students of rocks should have placed different emphasis on chemical composition, texture, mineralogical composition, age, mode of occurrence, and origin, as criteria, and should be of different minds regarding the desirability of a "natural classification" as opposed to an artificial one.

Early in the eighteenth century contributions to the knowledge of rocks were made by the few men who resisted the temptation to speculate and to dogmatize about things in general, and who confined their attention to a particular topic or a particular locality. In 1768 Linnaeus (1707-1778) extended his *Systema Naturae* to include the inorganic kingdom which he divided into rocks, minerals, and fossils. To each of these subdivisions was assigned an incongruous group of materials. As remarked by Cross, the most visible effect of this pioneer attempt to force inorganic substances into the scheme of species and genera provided for plants and animals was to furnish a theme for controversial debates and arguments for a century to come.

The outstanding figure among students of rocks of the eighteenth and early nineteenth centuries is Abraham Gottlob Werner (1749-1817), professor of mineralogy at Freiberg, whose enthusiasm, eloquence, skill in teaching, and clear methodical presentation attracted learners from all parts of Europe. Werner's views of rock genesis and of geological processes were antiquated even for his time, but his painstaking systematic examination of rocks led to a classification based on mineral composition (1786)—a feature common to modern schemes. He distinguished "simple" from "compound" rocks, recognized that some minerals were "essential" components of rocks and others "incidental" or "accessory," and clarified the subject by drawing the distinction between rock masses or strata (formations) and the rocks composing them, thus laying the foundation of modern descriptive petrography. During the first two decades of the nineteenth century, the knowledge of rocks as summarized in systems of classifications was carried as far as possible under the Wernerian scheme by Haüy (1801), Brongniart (1813), Cordier (1815), and their contemporaries who relied upon mineralogical composition and structure to indicate rela-

tionship to the exclusion of age, origin, and mode of occurrence.

But even during this period the problem of rock origin was prominently in mind. Were all rocks deposited by the ocean as chemical precipitates, as taught by Werner, or do deep-seated igneous rocks and lavas and sedimentary rocks indicate three modes of origin as taught by Hutton? Do the different kinds of rocks represent merely different ages of accumulation or are granite and sandstone made in all ages, even today? Are gneiss and schist original igneous rocks or altered sedimentary rocks? As if by common consent, the origin of the lava, basalt, was taken as a test case, and geologists, chemists, physicists, and even literary men and politicians divided into two camps—the Neptunists who contended that basalt is deposited from sea water were vigorously opposed by the Plutonists who believed in an igneous origin. Peace was declared in favor of the Plutonists soon after it was agreed that field observations were better weapons than arguments concocted in the library.

A distinct advance in the knowledge of rocks is recorded by two publications in the third decade of the nineteenth century.[5] Von Leonhard's "Characteristics of Rocks" (1823) is listed by Cross as "the first fairly consistent treatise on rocks" and its author as "unquestionably the foremost petrographer of his day, sharing with Alexander Brongniart the honor of placing the classification of rocks on a firm basis as a systematic science." Through the work of these able minds the confusion heretofore existing between minerals, rocks, and assemblages or groups of rocks (terranes and formations) was eliminated; the study of rocks as rocks (petrography and petrology) was shown to be a branch of learning with methods and purposes different from the study of strata and masses composed of rocks (stratigraphy); and the biological scheme of genera and species was discarded as inapplicable. These workers showed that structure, as well as mineralogical composition, is a significant feature and Brongniart suggests that geological origin may have value as a principle of classification. Both authors state with refreshing candor that fuller knowledge will show that many rocks have been given inappropriate places in the scheme of classification. To his major divisions, (1) heterogeneous rocks, (2) homogeneous rocks, (3) fragmental rocks, (4) loose rocks, Von Leonhard added a group, "rocks apparently homogeneous," to care for serpentine, pitchstone, and certain schists whose constituents were not visible to the unaided eye but which were not minerals. Brongniart subdivided "homogeneous rocks" into those with distinct known mineral species and those whose density precluded the recognition of constituents.

[5]Von Leonhard, K. C., Charakteristik der Felsarten, 1823.
Brongniart, Alexandre, Classification et caractères minéralogiques des roches homogènes et hétérogènes, Paris, 1827.

A new mode of treatment was introduced into the science of rocks by Carl Friedrich Naumann (1850 and 1858)[6]. Under the name *Petrography* he defined the scope of the science of rocks as a branch of Geology (or *Geognosie* as the term was then used) which could be studied from six standpoints: the constituents of rocks, the texture and structure of rocks, manner of occurrence, systematic description, genesis of rocks, and alteration of rocks. He introduced the classification: (1) crystalline rocks, (2) clastic rocks, (3) rocks neither crystalline nor clastic.

Von Cotta's contribution[7] (1855 and 1862) was the emphasis placed on geological mode of origin and the clear expression of the modern view that molten material poured from volcanoes and molten material formed deep within the crust of the earth may be crystallized into rock during any geological epoch and are not therefore indicative of age.

Frederick Senft (1857), probably impressed by the difficulty of determining the characteristics of dense rocks, minimized the value of mineralogical composition, texture, and structure as interpretative guides and developed an elaborate and highly artificial scheme based on chemical composition. But the master mind of the group whose attention was directed to the chemical relationship of rocks was Justus Roth. From a careful study of nearly 1,000 analyses he reached the conclusion (1861) that rocks cannot be represented by chemical formulae which coincide with mineralogical composition, and that the application of the chemical factor as a criterion in classification serves to separate rocks otherwise closely related. As a substitute he proposed that igneous rocks be grouped with reference to the abundance and kind of feldspar crystals contained within them.

An opposite conclusion was reached by Sheerer (1864) who expressed the belief that igneous rocks could be satisfactorily grouped in nine chemical types.

Zirkel's *Lehrbuch der Petrographie* (1866) and the philosophical discussions of Von Richthofen (1868) are substantially restatements of earlier views but are worthy of study as expressions of the usages and beliefs of the time and as the culmination of efforts to describe and to interpret rocks on the basis of superficial characteristics and approximate chemical analyses..

By 1870 the possibilities of increase of knowledge through the study of rocks appeared to have been exhausted; no further steps of advance seemed possible, for the components of fine-grained rocks, lavas, and schists were beyond the reach of observation and there ap-

[6]Naumann, C. F., Lehrbuch der Geognosie, 1850.

[7]Cotta, Bernhardt von, Rocks classified and described; a treatise on lithology (trans. P. H. Lawrence, 1866).

peared to be no satisfactory means of distinguishing the varieties of feldspars, the most abundant ingredient in the commonest rocks. Petrography had come to a blank wall. Further research involved the discovery of some method for more complete and exact observation. The need was met by the introduction of the compound polarizing microscope which brings to view and differentiates minerals even in apparently homogeneous rocks. The development of this instrument and of the means of preparing rocks for study marked the beginning of the golden age of descriptive petrography, the last quarter of the nineteenth century. The way had been blazed by Professor Nicol, the Scotch geologist, who invented the Nicol prism for polarizing light, attached it to a microscope, and devised a method for preparing thin sections of fossil wood (1828). The success of this method led Ehrenberg to the epoch-making discovery that chalk and marls and some limestones were composed of skeletons of organisms. Sorby (1850) used this method for determining the composition of sandstone and discussed its value for the study of igneous rocks. But to make a chip of hard rock sufficiently thin to be transparent seemed a hopeless task. It is a triumph of technical skill to cut from a black dense rock a section 1/1000 of an inch thick through which print may be read and which reveals to the microscope the minutest structures. The seemingly impossible has been accomplished and the modern geologist is placed in the position of the biologist with respect to the examination of microscopic objects of natural history. This method of research under the lead of Zirkel and Rosenbusch in Germany, Michel-Lévy, Barrois, and Lacroix in France, Bonney, Judd, and Rutley in England, E. S. Dana, G. H. Williams, and Iddings in America, promised so much that it soon enlisted an army of workers who added enormously to the knowledge of rocks and of the minerals composing them. During the closing years of the nineteenth century, microscopic description of rocks appeared to be the chief aim of petrographers.

About the beginning of the present century *Petrography* became *Petrology;* the science of the exhaustive description of rocks became the science of relations and meaning of rocks. The genesis of rocks and the factors that have brought about their geographic distribution and produced the hundreds of varieties are topics of interest to a modern student of petrology. The goal is in sight, but the best means of reaching the goal is not apparent. As in other lines of research, progress depends upon choice of method. Reliance on the petrographic microscope has revealed a new world to geologists, but it has obvious limitations. It is an instrument for collecting data, for refined and accurate description rather than for determining origins, and after all known rocks and rock-making minerals have been studied this method has served its main purpose. This stage nearly has been

reached. Twenty years ago most minerals, certainly all those of wide distribution, had been exhaustively studied and igneous rocks by the thousands had been minutely described and built into schemes of classification. Many sedimentary rocks and schists and gneisses also have been added to the list. Progress has been attained by the development of chemical methods of research in rock origins and rock-relationship. The pioneer work of Bischof (1846), the founder of chemical geology, Bunsen (1851) and Senft (1857), led the way to the researches of Roth, Clarke, and Hillebrand, and culminated in Washington's awe-inspiring volume "Chemical Analyses of Igneous Rocks" (1903), Cross, Iddings, Pirsson, and Washington's "Quantitative Classification of Igneous Rocks" (1903), and Clarke's "Data of Geochemistry" (4th ed. 1920)—three American works which are essential handbooks for geologists and chemists of all countries.

But while it is generally admitted that chemical composition is the most fundamental characteristic of rocks, it is obvious that the most precise determination of the chemical constituents of all the rocks in existence would not in itself explain the origin of rocks or contribute more than unrelated facts to the history of the earth. In order to gain the truths of rock history it is necessary to know the processes which cause the results and the conditions under which these processes operate. On the basis of chemical composition, by theoretical and to a small extent by experimental methods, interesting attempts were made during the last quarter of the nineteenth century to determine the order in which minerals crystallize from a molten mass (magma) and the conditions responsible for the differentiation of magmas into chemical groups. As at other stages in the history of petrology, the problem was recognized but the known methods were inadequate.

The gateway to further research was opened by physical chemistry. With the development of this new science and the consequent improvement in experimental methods came the possibility of reproducing in the laboratory the work of underground forces and of recording the stages through which rocks and minerals pass from undifferentiated masses of molten or liquid material to their final form as quartz, granite, or marble.

In view of modern developments it is interesting to recall pioneer experiments. To disprove the teaching of the all powerful German School of his day that basalt (lava) was precipitated from water, Sir James Hall in the year 1800 melted lavas from Etna and Vesuvius and allowed the mass to cool. Solid crystalline rock material resulted. Daubrée (1857) made quartz and feldspar from an aqua-igneous complex, proving that the conditions necessary to produce "granite-grained" igneous rock were moderate temperatures and presence of water vapor. Fouque and Michel-Lévy (1878) produced augite-

andesite with well-developed crystals by fusing selected ingredients in a dry state holding the fused mass at a high temperature for forty-eight hours then allowing it to cool. These brilliant researches of French geologists were carried still farther by Vogt and by other European scholars. But the world center for the experimental study of rock genesis is the Geophysical Laboratory at Washington[8] where under ideal conditions a corps of physicists, chemists, mineralogists, and petrologists are solving the deeper problems of rock genesis and rock relationship.

The Making of Mountains

Since the dawn of human history, even the uncritical observer must have noted that rock masses differ not only in color and composition but also in attitude; that some strata lie flat, others are tilted, still others are folded and buckled or broken. On the theory of a ready-made earth such facts occasioned no comment but as the evidence accumulated that changes large and small have affected the earth's surface, speculations regarding the causes and processes of rock disturbance and of the origin of mountains were in order.

To observers of the seventeenth century earthquakes were an all sufficient cause. Hooke (1688)[9] expressed the belief:

> Earthquakes have turned plains into mountains and mountains into plains, seas into land and land into seas, made rivers where there were none before, and swallowed up others that formerly were.

Woodward (1695)[10] cut the knot with the statement,

> the whole terrestrial globe has been taken to pieces at the flood and the strata settled down from this promiscuous mass.

Burnet[11] took the same view, and the state of knowledge of the times may be judged from the fact that his theory of the earth (1690) thoroughly unsound in matter, method and conclusions was praised in a Latin ode by Addison and highly commended by Steele.

During the eighteenth century the view prevailed that all rocks were originally horizontal and that departures from this attitude were local and sufficiently accounted for by landslides, by cavities into which rocks fell, by volcanoes, and by original deposition in addition to the ever ready earthquake or flood which played the title rôle. As late as 1823 the easterly dip of the Connecticut River sandstone is ascribed by Hitchcock to "some Plutonian convulsion."[12]

[8]Carnegie Geophysical Laboratory, Washington. For a sketch of the scope and contributions of this institution, see Sosman, R. B., The work of the geophysical laboratory of the Carnegie Institution of Washington: A century of science in America, pp. 284-287, Yale University Press, 1918.

[9]Hooke, Robert, Posthumous works, ed. R. Waller, London, 1705.

[10]Woodward, John, Essay towards a natural history of the earth, 1695.

[11]Burnet, Thomas, Telluris theoria sacra, or Sacred theory of the earth, London, 1681. Eng. trans. 1684-1689.

[12]Hitchcock, Edward, Geology, etc., of the Connecticut Valley; *Am. Jour. Sci.*, VI, 74, 1823.

Toward the close of the eighteenth century belief in the ability of streams and waves to corrade the surface, and to carry debris into the ocean, gained general acceptance. This belief carried to its logical conclusion meant that all dry land would ultimately disappear unless some forces were acting to re-elevate the continents. Earthquakes might break strata and volcanoes scatter the material about, but their effect is local and it was difficult to imagine how they might raise and depress the sea floor, build high mountains, or even produce the folds and contortions characteristic of many regions. Even the advocates of the Noachian flood were forced to depart from the literal description and call in comets and sudden shifting of the earth's axis to account for the seemingly disorganized earth with marine shells miles high on mountains. It was seen that some new mechanism must be devised, but the accepted teachings of the eighteenth and early nineteenth centuries allowed no place for an additional agent. Out of this impasse geology was led by James Hutton—successful physician, farmer, and manufacturing chemist. Discarding speculation and tradition and all concern for origins of things, this "patient, enthusiastic, level-headed devotee of science" observed phenomena and processes, and developed a logical theory which lies at the base of modern dynamical geology. Hutton's "Theory of the Earth with Proofs and Illustrations" (1795) and its companion volume, Playfair's "Illustrations of the Huttonian Theory" (1802), are classics in geologic literature, which are scarcely out of place in a modern class room. The scheme as outlined by Hutton is simple and convincing. Observation taught him that the features of the earth are not rigid and immutable but are continuously undergoing changes. Rocks decay, soil is swept away by streams, coasts are worn down, and all loose material is carried to the sea. In time the solid lands must disappear. The debris is deposited on the ocean floor forming layers in which remains of organisms are embedded. The material for making future lands is thus prepared. But to be recovered from the sea and built into continents these sediments must be elevated. In searching for an agent capable of causing uplift, Hutton dismissed as phantoms the "convulsions of nature," "emanations," and "universal debacles" of his contemporaries and predecessors. Going once more to the field, he observed that many rocks are not stratified and many are bare of fossils and that these rocks show unmistakable evidence that they were once in a molten state; in fact, that some of the igneous materials have come up from below, penetrated the surrounding rocks, and altered their appearance and composition. Deep within the earth, therefore, heat must prevail and the sudden expansion of rocks induced by heat not only produced volcanoes but lifted the overlying rock masses. Rugged mountains, broken and tilted strata, and folds are witnesses to these gigantic upheavals.

Hutton's teachings were a half century ahead of his time and made slow headway. Though supported by the nebular hypothesis of a cooling globe, by the testimony of miners that heat increases with depth, and by the evidence of volcanoes as presented by Desmarest (1725-1815) and by Scrope (1823), the hypothesis of universal and subterranean heat was ignored or combatted by the strongly entrenched Wernerian school which clung to the view that all rocks are formed from water, that mountains are gigantic crystalline aggregates made where they stand, and that the earth is cold to the center. Professor Jameson, a colleague of Playfair at Edinburgh University, writing in 1808[13], calls the researches of Hutton, Playfair and Hall "monstrosities" and remarks: "It is therefore a fact that all inclined strata with few exceptions have been formed so originally and do not owe their inclination to subsequent change." Fortunately for science Hutton was followed by Lyell (1797-1875). Taking for his text the saying of Hutton, "Amid all the revolutions of the globe, the economy of nature has been uniform," Lyell expounded and systematized the theories of his master, gathered new facts, pointed out errors, and through his "Principles of Geology" guided the thought of students during the second quarter of the nineteenth century. Lyell's chief contribution was the development of the thesis that the forces operating on and within the earth during past time are the same as those of today; that knowledge of past events is to be gained by studying present processes. The building of mountains and continents, the folding and breaking of strata, the making of igneous and sedimentary rocks, and the entombment of fossils are proceeding as rapidly and in the same manner as in other ages. There have been no "gigantic cataclysms" or "devastating floods"; all processes have been orderly and uniform in degree and in kind. The emergence and submergence of coasts, the changes of level associated with earthquakes, are the rule not exceptions, and do not involve unusual forces.

> The land has never in a single instance gone down suddenly for several hundred feet at once. . . Great but slow oscillations have brought dry land several thousand feet below sea and raised it thousands of feet above. Places now motionless have been in motion and places of present active movements were formerly stationary.

Although this doctrine of "uniformitarianism" was carried by Lyell somewhat beyond the modern viewpoint the road to progress was cleared of fantastic speculations.

Hutton and Lyell considered heat combined with pressure sufficient cause for vertical uplifts of parts of the earth's surface. The analyses of these processes have absorbed the attention of structural geologists down to the present day. In 1833 the brilliant French scholar, Elie de Beaumont (1798-1874), expressed the view that the earth is a fused

[13]Jameson, Robert, Elements of geognosy, Edinburgh, 1808.

mass covered by an envelope of cooled rock "thinner in proportion than the shell of an egg." In adjusting itself to the cooling interior this crust became wrinkled. From time to time portions of the crust collapsed along definite lines of fracture. At such times the rocks are subjected to great lateral pressure; the unyielding ones are crushed, the pliant ones bent and forced to pack themselves into smaller space. The readjustment of the shell to the shrinking interior causes portions of the crust to be squeezed upward as wrinkles or folds which we call mountain ranges. By reference to the surrounding rocks, the date of the mountain's birth is obtained.

These theoretical views although erroneous and discounted even during the life time of their author marked an important advance, for through them came the idea of mountain folding by lateral compression. As treated by James D. Dana,[14] this conception grew into a consistent theory of mountain origin and structure which has received universal acceptance. In brief, this theory is as follows: Materials for the future mountain system are eroded from a land mass and deposited in a progressively sinking trough to thickness of thousands of feet. After long ages the sediments in the trough are compressed laterally against the relatively solid old land; the shortening, amounting to many miles (Appalachians, 40 miles; Alps, 74), is made possible by folding or by forcing parts to override other parts. During and after the periods of folding and faulting the newly born mountain range is eroded into features which are recognized as ridges, peaks and valleys. These processes, which in detail are enormously complicated, involve regional upwarps and downwarps which are recorded over wide areas. Largely through a study of mountain ranges with their faults and folds and enormous thicknesses of disturbed sedimentary and igneous rocks has come the modern view of the fundamental structural relations: that the earth is not a liquid or molten mass covered with a crust, but a globe as rigid as a ball of steel or glass of equal dimensions yet "elastic" or "pliable" enough to yield under the weight of even a moderate load.

Interpretation of Natural Scenery

A discussion of the principles and processes involved in sculpturing the earth surface was futile on the hypothesis of a ready-made earth whose features were unchangeable except when modified by catastrophic action. The belief in the Deluge as the one great event in geological history effectually checked investigation of the work of rivers, glaciers, wind, and the atmosphere in producing the variety of forms that constitute natural scenery. It is therefore not surprising that physiography, whose essence lies in the belief that present land forms rep-

[14]Dana, J. D., Manual of geology, Philadelphia, 1863, 3d ed., 1880.

resent merely a stage in the orderly development of the earth's surface features, should have attained the dignity of a science within the past quarter century; nor that the speculations of Aristotle, Herodotus, Strabo, and Ovid, and the illustrious Arab, Avicenna (980-1037), unchecked by appeal to facts but also unopposed by priesthood or popular prejudice, are nearer to the truth than the intolerant controversial writings of the intellectual leaders of the late Middle Ages whose touchstone was orthodoxy. Steno (1638-1687) mildly suggested that surface sculpturing, particularly on a small scale, is largely the work of running water, and Guettard (1715-1786) grasped the fundamental principles of denudation; but nearly eighteen centuries had elapsed before Desmarest, the father of physiography, presented proofs that valleys are made by rivers and that a landscape passes through clearly defined stages of development.

Desmarest's teachings were strengthened and expanded by DeSaussure (1740-1799)[15], the originator of the term, "geology," who saw in the intimate relation of Alpine streams and valleys the evidence of erosion by running water (1786).

These works from the acknowledged leaders of geological thought of the period aroused singularly little interest on the Continent, and Lamarck's volume on denudation (Hydrogéologie), which appeared in 1802, although an important contribution, sank out of sight. But the seed of the French school found fertile ground in Edinburgh, the hub of the geological world at the close of the eighteenth century. Hutton's "Theory of the Earth, with Proofs and Illustrations," in which the guidance of DeSaussure and Desmarest is gratefully acknowledged, appeared in 1795. The original publication aroused only local interest, but when placed in attractive form by Playfair[16], the problem of the origin and development of land forms assumed a permanent position in geological thought. Steps in the analysis and solutions of these problems may be illustrated by tracing the growth of ideas regarding valleys and features produced by glaciation.

In the interpretation of valleys little progress was made during the first fifty years of the nineteenth century. Physiographic literature shows that the clear reasoning of Desmarest, DeSaussure, Hutton, and Playfair, firmly buttressed by concrete examples, was insufficient to overcome the belief that valleys are ready-made or result from cataclysms and that the corrugations and irregularities of mountain surface are remnants of the primeval earth. The principles laid down by these clear-sighted leaders were too far in advance of their time to secure general acceptance. In a paper with the significant title, "Burst-

[15]Saussure, H. H. de., Voyage dans les Alpes, 1779-1796.

[16]Playfair, John, Illustrations of the Huttonian theory, 1802; trans. into French by C. A. Bassett, 1815.

ing of Lakes Through Mountains," Wilson (1821) asks: "Is it not the best theory of the earth, that the Creator, in the beginning, at least at the general deluge, formed it with all its present grand characteristic features?"[17]

In 1823 Buckland[18] wrote:

> . . . The general belief is that existing streams, avalanches and lakes, bursting their barriers, are sufficient to account for all their phenomena. It is now very clear to almost every man, who impartially examines the facts in regard to existing valleys, that the causes now in action . . . are altogether inadequate to their production; nay, that such a supposition would involve a physical impossibility. . . . We do not believe that one-thousandth part of our present valleys were excavated by the power of existing streams.

Similar views expressed in scientific journals of Europe and of America by the leaders of geologic thought, including Hitchcock (1824),[19] Phillips (1829),[20] Lyell (1833), Conrad (1839),[21] Darwin (1844),[22] Warren (1859),[23] and Lesley (1862).[24]

By the middle of the nineteenth century opinion regarding valleys had become standardized somewhat as follows: the position of many valleys is determined by original surface inequalities or by later fractures in the earth's crust; most of them are intimately associated with earthquakes, bursting of lakes, or the sudden upheavals or depressions of the land; valleys of erosion are chiefly the work of the sea, but rivers may perform similar work on a small scale.[25] The extent of the wandering from the guidance of DeSaussure and Playfair after the lapse of fifty years is shown by students of Switzerland. Alpine valleys to Murchison (1851) were bays of an ancient sea; Schlaginweit (1852) found regional and local complicated crustal movements a satisfactory cause; and Forbes (1863) saw only glaciers.

The truths expounded by Desmarest and Hutton were reestablished by James D. Dana,[26] who in 1850 amply demonstrated that valleys on

[17]Wilson, J. W., Bursting of lakes through mountains: *Am. Jour. Sci.*, III, 253, 1821.

[18]Buckland, William, Reliquiæ diluvianæ: *Am. Jour. Sci.*, VIII, review, 150, 317, 1824.

[19]Hitchcock, Edward, Geology, mineralogy, and scenery of regions contiguous to the Connecticut River, with a geological map and drawings of organic remains (etc.): *Am. Jour. Sci.*, VII, 1-30, 1824.

[20]Phillips, John, Geology of Yorkshire: *Am. Jour. Sci.*, XXI, 17-20, 1832.

[21]Conrad, T. A., Notes on American geology: *Am. Jour. Sci.*, XXXV, 237-251, 1839.

[22]Darwin, C. R., Geological observations, etc., during the voyage of the "Beagle," London, 1844.

[23]Warren, G. K., Explorations in Nebraska and Dakota: *Am. Jour. Sci.*, XXVII, Review, 380, 1859.

[24]Lesley, J. P., Observations on the Appalachian region of southern Virginia: *Am. Jour. Sci.*, XXXIV, 413-415, 1862.

[25]For a fuller statement of the views regarding origin of valleys, see Gregory, H. E., Steps of progress in the interpretation of land forms: A century of science in America, pp. 124-152, Yale University Press, 1918.

[26]Dana, J. D., On denudation in the Pacific: *Am. Jour. Sci.*, IX, 48-62, 1850.

——————, On the degradation of the rocks of New S. Wales and formation of valleys: *Am. Jour. Sci.*, IX, 289-294, 1850.

the Pacific islands owe neither their origin, position nor form to the sea or to structural factors, but are the work of existing streams which have eaten their way headwards. Even the valleys of Australia cited by Darwin as type examples of ocean work are shown to be products of normal stream action. Dana went further and gave a permanent place to the Huttonian idea that many bays, inlets, and fiords are but the drowned mouths of river-made valleys. The theory that valleys are excavated by streams which occupy them received strong support from study of the Rocky Mountain gorges (1862) and gained all but universal acceptance after Newberry[27] called attention to the lesson to be learned from the canyons of Arizona:

> Like the great cañons of the Colorado, the broad valleys bounded by high and perpendicular walls *belong to a vast system of erosion, and are wholly due to the action of water*. . . The first and most plausible explanation of the striking surface features of this region will be to refer them to that embodiment of resistless power—the sword that cuts so many geological knots—volcanic force. The Great Cañon of the Colorado would be considered a vast fissure or rent in the earth's crust, and the abrupt termination of the steps of the table-lands as marking lines of displacement. This theory though so plausible, and so entirely adequate to explain all the striking phenomena, lacks a single requisite to acceptance, and that is *truth*.

With these stupendous examples in mind, the dictum of Hutton seemed reasonable: "There is no spot on which rivers may not formerly have run."

Contributions to physiography between 1850 and 1870 reveal a tendency to accept greater degrees of erosion by rivers, but the necessary end-product of subaerial erosion—a plain—is first clearly defined by Powell (1875),[28] who introduced the term "base level," which may be called the germ word out of which has grown the "cycle of erosion," the master key of modern physiographers.

Analysis of Powell's view has given definiteness to the distinction between "base level," an imaginary plane, and a "nearly featureless plain," an actual land surface, the final product of subaerial erosion. Following their discovery in the Colorado Plateau Province, denudation surfaces were recognized in Pennsylvania by McGee,[29] and in Connecticut by Davis (1889)[30] who introduced the term "peneplain," "a nearly featureless plain," for the upland of southern New England developed during Cretaceous time.

Long before the days of Powell "plains of denudation" had been clearly recognized by English geologists who considered them products of marine work. The contribution of American students is not that peneplains exist but that many of them are the result of normal

27Newberry, J. S., Colorado River of the West: *Am. Jour. Sci.*, XXXXIII, review, 387-403, 1862.

28Powell, J. W., Exporation of the Colorado River of the West, 1875.

29McGee, W. J., Three formations of the Middle Atlantic Slope: *Am. Jour. Sci.*, XXXV, 120, 328, 367, 448, 1888.

30Davis, W. M., Topographic development of the Triassic formation of the Connecticut Valley: *Am. Jour. Sci.*, XXXVII, 423-434, 1889.

subaerial erosion. More precise field methods during the past decade have revealed the fact that no one agent is responsible for the land forms classed as peneplains; that not only rivers and ocean, but ice, wind, structure, and topographic position must be taken into account.

The recognition of rivers as valley-makers and of the final result of their work necessarily preceded an analysis of the process of subaerial erosion. The first and last terms were known, the intermediate terms and the sequence remained to be established. Significant contributions to this problem were made by Jukes' (1862) discussion of "lateral" and longitudinal" valleys, Powell's description of antecedent and consequent drainage (1875), and Gilbert's analysis of land sculpture in the Henry Mountain (1880). But the master papers are by Davis,[31] who introduces an analysis of land forms based on structure and age by the statement:

> Being fully persuaded of the gradual and systematic evolution of topographical forms it is now desired . . . to seek the causes of the location of streams in their present courses; to go back if possible to the early date when central Pennsylvania was first raised from the sea, and trace the development of the several river systems then implanted upon it from their ancient beginning to the present time.

That such a task could have been undertaken only three decades ago and today be considered a part of every-day field work shows how completely the lost ground has been regained and how rapid has been the advance in the knowledge of land sculpture since the canyons of the Colorado Plateau were interpreted.

One of the most interesting chapters in geological history is the origin and development of the theory of continental glaciation, which grew out of the attempt to explain the presence of "erratic" bowlders strewn over the surface in "obviously unnatural" positions. As stated by Silliman (1821):[32]

> The almost universal existence of rolled pebbles, and boulders of rock, not only on the margin of the oceans, seas, lakes, and rivers; but their existence, often in enormous quantities, in situations quite removed from large waters; inland,—in high banks, imbedded in strata, or scattered, occasionally, in profusion, on the face of almost every region, and sometimes on the tops and declivities of mountains, as well as in the valleys between them; their entire difference, in many cases, from the rocks in the country where they lie—rounded masses and pebbles of primitive rocks being deposited in secondary and alluvial regions, and vice versa; these and a multitude of similar facts have ever struck us as being among the most interesting of geological occurrences, and as being very inadequately accounted for by existing theories.

To this list of features now recognized as characteristic of glacial drift are to be added jumbled masses of "diluvium," ridges of gravel, "kettles" in sand plains, polished and striated rock, and thick beds of

[31]Davis, W. M., The rivers and valleys of Pennsylvania: *Nat. Geog. Mag.*, I, 183-253, 1889.

————————, The rivers of northern New Jersey with notes on the classification of rivers in general, ibid, II, 81-110, 1890.

[33]Silliman, Benjamin, Review of Hayden's geological essays: *Am. Jour. Am. Jour. Sci.*, III, 49, 1821.

"unhardened pudding stone" (till). Even Lyell, the great exponent of uniformitarianism, appears to have lost faith in his theories when confronted with facts for which known causes seemed inadequate.

The interest aroused by the phenomena now attributed to ancient glaciers is attested by scores of titles in scientific and literary periodicals of the first four decades of the nineteenth century. With little knowledge of existing glaciers, of areal distribution, structure and composition of drift, all known forces were called in: weathering, catastrophic floods, ocean currents, waves, icebergs, glaciers, wind, and deposition from a primordial atmosphere. Even human agencies were not discarded. But the controversy ranged chiefly about floods, icebergs, glaciers, and earth shaking catastrophes.

The catastrophes favored by most geologists were the Deluge, and floods of water violently released from the interior of the earth or caused by sudden upheaval of mountains. "We believe," says Silliman (1824) "that all geologists agree in imputing . . . the diluvium to the agency of a deluge at one period or another"[33]—a conclusion which rested in no small way upon Hayden's[34] well-known treatise on "diluvium" (surficial deposits, glacial drift). The objection to the theory of "debacles" and resistless world-wide currents is not only its grotesque assumptions and processes but also its complete disregard of observable phenomena. Its strength lay chiefly in its supposed confirmation of the Biblical record and it is perhaps natural that the way to a saner view should have been pointed out by intelligent laymen rather than by leaders of thought bound by authority and tradition. Unbiased observation is an essential condition of progress.

In 1823[35] Granger speaks of the glacial striæ on the shore of Lake Erie as

> having been formed by the powerful and continued attrition of some hard body. . . To me, it does not seem possible that water under any circumstances, could have effected it. The flutings in width, depth and direction, are as regular as if they had been cut out by a grooving plane. This, running water could not effect, nor could its operation have produced that glassy smoothness, which, in many parts, it still retains.

The first unequivocal statement that ice is an essential factor in the formation and transportation of drift comes from another layman, Peter Dobson (1826),[36] who concludes a series of accurate detailed observations on the polished and striated bowlders embedded in the Connecticut till with the remark:

> I think we cannot account for these appearances, unless we call in the aid of ice along with water, and that they have been worn by being suspended and carried in ice, over rocks and earth, under water.

[33]Silliman, Benjamin, Review of Hayden's geological essays: *Am. Jour. Sci.*, VII, 211, 1824.

[34]Hayden, H. H., Geological essays, 1-412, 1821: *Am. Jour. Sci.*, III, 47-57, 1821.

[35]Granger, Ebenezer, Notice of a curious fluted rock at Sandusky Bay, Ohio: *Am. Jour. Sci.*, VI, 180, 1823.

[36]Dobson, Peter, Remarks on bowlders: *Am. Jour. Sci.*, X, 217-218, 1826.

The glacial theory makes its way into geological literature with the development by Agassiz (1837) of the views of Venetz (1833) and Charpentier (1834) that the glaciers of the Alps once had greater extent. The bold assumption was made that the surface of Europe as far south as the shores of the Mediterranean and Caspian seas was covered by ice during a period immediately preceding the present. The kernel of the present glacial theory is readily recognizable in these early works, but it is wrapped in a strange husk: the Alps were assumed to have been raised by a great convulsion under the ice and the erratics to have slid to their places over the newly made declivities. The publication of the famous "Etudes sur les Glaciers" (1840), remarkable alike for its clarity, its sound inductions, and wealth of illustrations, brought the ideas of Agassiz into prominence and inaugurated a thirty years' war with the proponents of floods and of icebergs. The outstanding objections to the theory were the requirement of a frigid climate and the demand for glaciers of continental dimensions; very strong objections for the time when fossil evidence was not available, the great polar ice sheets unexplored, and the distinction between till and water-laid drift had not been established.

So fully does the glacial hypothesis account for observed phenomena that it received the sympathetic attention of leading geologists especially in America. As the evidence accumulated opposition disappeared and by 1875 the belief in the former wide extent of land ice was firmly established.[37] The next step forward was the determination of the extent of glacial drift—a series of field studies that have produced the modern maps of glaciated areas and led to the interesting conclusion that the "ice age" was not the record of the advance and retreat of one great continental glacier, but that it is divided into epochs; that several retreats are required to account for the phenomena of buried soils and overlapping ice laid deposits. In 1883 Chamberlin[38] presented his views, under the bold title "Preliminary Paper on the Terminal Moraine of the Second Glacial Epoch," which initiated the discussion that led to the recognition of glacial deposits of different ages and the features of interglacial periods. Field studies during the last quarter century have demonstrated five glacial stages in America and four in Europe.

Within the present generation sculpture by glaciers has received much attention and has involved a reconsideration of the ability of ice to erode which in turn involves a crystallization of views of the mechanics of moving ice. The inadequacy of structural features or of

[37]Gregory, H. E., Steps of progress in the interpretation of land forms: A century of science in America, pp. 122-152, Yale University Press, 1918.

[38]Chamberlin, T. C., Preliminary paper on the terminal moraine of the second Glacial period: *U. S. Geol. Survey, Third Ann. Rept.*, pp. 291-402, 1883.

river corrasion to account for flat-floored, steep-walled gorges, hanging valleys, and many lake basins, has led to the present fairly general belief in the long neglected views of Ramsay that glaciers are powerful agents of rock sculpture. The details of the process, particularly of cirques, are not yet fully understood.

Meaning of Fossils

From the time when fossils received general recognition as the remains of extinct organisms, they have been examined from two viewpoints. One group of students (stratigraphers) are interested in fossils as objects which characterize geological epochs and by means of which true succession and relative ages may be determined. The other group (paleozoologists and paleobotanists) find the supreme value of fossils in their bearings on the problems of origin, development, and evolution of living forms. It is this biological aspect which has aroused an almost universal interest in fossils, brought the teachings of geology into zoological laboratories and medical schools, and furnished material for controversy to theologians and philosophers. The founders of paleontology, Blumenbach (1803-1816), Schlotheim (1804), Sternberg (1804), Cuvier (1808), Lamarck (1815-1822), and Brongniart (1822), attained success by applying the methods of comparative anatomy and botany, and the subject found an assured position through the work of Buckland (1836), Mantell (1844), Pictet (1844-1846), Geinitz (1846), Quenstedt (1852), and Richard Owen (1860)—all primarily biologists. Vertebrate paleontology especially has been treated as a branch of comparative anatomy concerned primarily with fossil bones and teeth, but its contributions have brought the civilized world to a belief in the theory of organic evolution.

Fossils were correctly considered by the Greeks and Romans as remains of plants and animals, but their presence in the rocks was ascribed to gigantic inundations which had brought marine animals far inland. Avicenna (980-1037), the great Arabian scholar, thought fossils were the unfinished work of *vis plastica,* a creative force that changed inorganic substances to organic; the living form had been produced but no life given it. To George Bauer [Agricola] (1494-1555), and to Mattioli (1548) fossils were "solidified accumulations from water" like limestone, or converted into stone by a certain *succus lapidescens* believed to reside in water; to the anatomist Fallopio fossil teeth were concretions and fossil shells the result of "fermentations" and "exhalations from the soil"; to Olivi of Cremona they were mere sports or freaks; Lister (1638-1711) taught that each rock stratum produces its own fossils; Mercati, museum assistant to Pope Sixtus V, thought them seeds of the stars; and the English antiquary

Lhuyd (Luidius) sought their origin in seed-bearing vapors originating in the sea. These typical seventeenth century ideas of the nature of fossils are to be contrasted with those of Leonardo da Vinci (1452-1519) and Fracastora (1483-1553) who insisted that fossils are organisms which once lived where now found, and which owe their preservation to burial in mud.

The conclusions of these Italian scholars who ridiculed the notion that fossils descended from stars or were formed in the earth by some mysterious creative force were disregarded or treated as "vaporings of disordered minds"; Bernard Palissy (1499-1589) who near the close of the sixteenth century gave a correct explanation of petrified wood, fossil fish and molluscs was vigorously denounced as a heretic. Even the teachings of the remarkable scholar, Nicholaus Stensen (Nicolas Steno, 1631-1687), whose little pamphlet "*De solido intra solidum naturaliter contento*" (1669) is the high water mark of seventeenth century geology, made little impression and was soon forgotten, and at the beginning of the eighteenth century fossils were generally considered mineral curiosities—"formed stones," "figured stones"—and chance imitations of living forms.

Fortunately the disputes regarding the nature of fossils encouraged the search for fossils and led to a number of valuable works in which fossils were faithfully described and represented by drawings. Publications descriptive of fossils of particular regions, monographs on selected groups, and general treatises on classification and nomenclature appeared in France, England, Germany, Switzerland, and Italy during the early part of the eighteenth century. Through the labors of Scheuchzer[39] and many supporters, Johann Baier[40] and especially John Woodward,[41] and Knorr and Walch,[42] whose handsome four volume treatise is the paleontological masterpiece of that period, trilobites, brachiopods, molluscs, crinoids, sponges, crabs, fishes and vertebrate bones were made known to the scientific world. The accumulated evidence was conclusive and at the middle of the eighteenth century no scholar of repute looked on fossils as the result of inorganic forces.

With the recognition of fossils as the remains of living beings, the three century discussion of the origin of fossils assumed new form. Are these objects the *relictae* of animals and plants now living or do they represent peculiar races of animals and plants which formerly inhabited the earth? Have they originated where found or have they been transported to their present resting places, and if transported,

[39]Scheuchzer, J. J., Specimen lithographie helveticae curiosae, 1702.

[40]Baier, Johann, Oryctographica norica, 1712.

[41]Woodward, John, Natural history of the earth and terrestrial bodies, etc., London, 1695.

[42]Knorr, G. W., and Walch, J. E. F., Die Sammlung von Merkwürdigkeiten der Natur und Alterthümer des Erdbodens.

by what agency? With the fauna of half the earth's surface and the life of the ocean unknown it was but natural to assume that fossil snails and oysters and leaves belonged to species of animals and plants which still flourished in some unexplored part of the world. It was commonly believed that the only animals in existence were those made during the days of creation and that none had disappeared from the world. Thus the bones of the ground sloth (*Megalonyx jeffersoni*) described by Thomas Jefferson were believd by him to be the remains of some sort of a lion still living in the Allegheny Mountains. But the hope of finding living specimens to match the skeletons embedded in the rock resulted in disappointment and in the search for other explanations the theory of great catastrophes which overwhelmed the inhabitants of all or parts of the earth gained the support of the leading minds toward the close of the eighteenth century. Great inundations of the sea, terrific earthquakes, and gigantic volcanic eruptions all had their supporters, but the belief in Noah's flood enlisted the most faithful adherents. The biblical flood not only swept the earth of living forms, but scattered their remains far and wide and left them buried in jumbled heaps in the sands and muds deposited by the onrushing currents. Warmly approved by the church, the "diluvialists" occupied a strong position in the scientific world well into the nineteenth century. Even the great Cuvier (1821) lent support to the believers in the flood and Buckland's treatise on the *Organic Remains contained in Caves, Fissures and Diluvial Gravel, and on other phenomena Attesting the Action of a Universal Deluge*, bears the date 1823.

With a wider recognition of the fact that fossils are not restricted to sands and gravels and muds which might have been deposited within the past few thousands of years, but are found embedded in firm rock on plains and seashore and mountain tops and are revealed by mine shafts, wells, tunnels, and excavations for buildings, the diluvial hypothesis assumed yet another form. Noah's flood was retained, but was given the position of the last of a series of great catastrophes which overwhelmed the world.

Under the lead of the French paleontologists, cordially supported by their English and American colleagues, the "catastrophists" held sway during the first six decades of the nineteenth century. They clearly recognized that fossils in a given formation differed in kind from those in the overlying and underlying strata, but explained these facts on the theory that the period represented by each of these formations witnessed the complete disappearance of animal and plant life of the world. The fossils of the next higher strata were the remains of newly created beings. Each species was a separate creation. The simplicity of forms of the earlier creations compared with the complexity of form and structure of the fossils of later creations appears

to have been ascribed to progressive skill of the Creator rather than to the progressive development of species.

Cuvier, the leader of the catastrophic school, is the outstanding figure among the paleontologists of the first half of the nineteenth century. As a biologist he established comparative anatomy as a distinct branch of science and formulated the principles and methods still in vogue for the study of fossil vertebrates. Through his influence systematic research replaced disorganized observation. His conception of the correlation of parts, that structure and function are interdependent, is the guiding principle in modern paleontology, and makes it possible to reconstruct an extinct animal from fragmentary remains found in the rocks or even from a single bone or tooth. His work shows a progression from description of individual bones to reconstruction of whole skeletons, and on to the grouping of extinct forms into species, genera, and orders. The wealth of fossil material embedded in the gypsum deposits of the Paris Basin "enabled him to prepare the first reconstructions of fossil vertebrates ever attempted and to bring before the eyes of his contemporaries a world peopled with forms which were utterly extinct."[43] To bring to the laboratory a miscellaneous assemblage of fossil bones and by the strict application of scientific method supply the missing parts until there appears an animal never before seen by human eye, may be considered one of the great achievements of the human mind. Little wonder that Cuvier's demonstrations revolutionized the thought of his day and made a deep and lasting impression. Paleontological views before the days of Darwin were essentially the views of Cuvier and his devoted disciples. Most of the epoch-making contributions of the Cuvierian school have remained undisputed but the contention that species are immutable is strangely out of harmony with modern views.

When the Cuvierians left the solid ground of their field of comparative anatomy they parted company with contemporary thinkers in other branches of geology and entered the bog already thickly populated with philosophers, theologians, and mystics of ancient and medieval times. Unconsciously and with different terminology, they gave their approval to Indian, Egyptian, and early Church beliefs in earth catastrophes followed by recreations—periods of disaster interspersed with millenia. There was no recognition of the orderly development of the earth and its inhabitants resulting from the operation of natural laws.

The publication of Darwin's "Origin of Species," 1859, marks the beginning of the evolutionary period in the study of fossils. The fixity of species was replaced by the evolution of species; recurrent

[43]Lull, R. S., On the development of vertebrate paleontology: A century of science in America, Yale University Press, 1918, p. 219.

catastrophes which necessitated new creations retired in favor of orderly development; and supernatural agencies were discarded. This revolutionary change in thought was foreshadowed by the teachings of a few bold spirits and the transition from catastrophism to evolution made easier by evidence accumulated during previous decades.

By 1856, two thousand fossils from strata later than the Carboniferous were known in America; in Europe more than 20,000. A study of this material led to the recognition of the facts that the individuals that compose a species are "endlessly diverse" (Dana); "that fossils from two consecutive formations are far more closely related than are the fossils of two remote formations" (Asa Gray); "that when species are arranged in a series and placed near to each other with due regard to their natural affinities they each differ in so minute a degree from those next adjoining that they almost melt into each other" (Lyell). And during the catastrophic period men were not lacking who accepted the evidence of transition in the organic world and followed it to its logical conclusion. Aristotle's views are singularly like those of modern time and Erasmus Darwin (1731-1802), grandfather of Charles Darwin, consistently taught that variations in species arise within organisms in response to environmental influences. Comte de Buffon (1707-1788) grasped the idea that life descends continuously from other life and is modified by geographical isolation, but only the industrious and serious-minded can separate the wheat from the chaff in the 44 volumes of his entertaining Histoire Naturelle (1749-1804).

Among evolutionists of Pre-Darwin days, Chevalier de Lamarck 1744-1829) stands first. For fifty years he was a firm believer in catastrophes and recreations but in later life, in the face of strong opposition, he gave the full weight of his knowledge and experience to the support of the theory of descent and inheritance of acquired characters. His teachings are so unmistakably clear and so sharply contrasted with the contentions of the catastrophists that Lamarck is justly regarded as the founder of the evolutionary school. Lamarck's ideas were kept alive by a group of earnest but unconvincing followers including Geoffroy Sainte-Hilaire and the poet Goethe, but such men were no match for the gifted scientists of the catastrophic school, supported as they were by the church and by public opinion. Even the *Vestiges of the Natural History of Creation* by Robert Chambers (1802-1871), the most discussed book of the time, failed to uproot traditional beliefs, and by 1850 the evolutionary theory was pronounced "dead" by the leading writers of the time.

The resurrection came with the publication of Darwin's *Origin of Species,* doubtless the most influential book of the nineteenth century. No wonder that Darwin's views were received with dismay and

aroused strenuous and bitter opposition, for their acceptance gave the death blow to creationists, placed man among the animals, and otherwise undermined the supposedly plain teachings of Scripture. The theory early received the support of Hooker, Huxley, and Herbert Spencer in England, and Asa Gray in America. Among its American opponents were James D. Dana, who later modified his opinion, and Louis Agassiz, who held his disapproval through life. That part of Darwin's theory which related to the progressive development of *living* plants and animals aroused little opposition, for improvements produced by the breeding of domesticated animals were well understood; but the testimony of the rocks that the lineal ancestors of existing animals are constituents of strata laid down millions of years ago was quite another matter.

The scientific opponents of evolution relied mainly on the fact, uncontested by geologists, that the successive strata did not disclose an unbroken series of modified forms—there were many "missing links" in the supposed chain of development. In this connection the discoveries of American vertebrate paleontologists make an interesting chapter. Beginning with 1870, Leidy, Cope, Marsh, followed by a group of workers of the present generation, unearthed the profusion of vertebrate remains from Tertiary, Cretaceous, and Jurassic beds which have made famous the collections in the American Museum of Natural History and the Peabody Museum at Yale. Professor Marsh alone found the remains of about 200 birds with teeth, 160 mammals, and hundreds of flying, swimming, and walking reptiles varying in size from guinea pigs to monsters 80 feet long. These collections bridged the gap between reptiles and birds and indicated the common ancestors for animals now recognized as distinct species.

Down through successive geological epochs the modern horse was traced through transitional forms to a four-toed ancestor, the size of a fox, which flourished during the Eocene. Such evidence could not be disregarded. In reviewing the work of Marsh, Huxley who previously had pointed out the insufficiency of the paleontological evidence, declared that "the evolution of existing forms of animal life from their predecessors is no longer an hypothesis but an historical fact" (1876).

Like other animals of the modern world, man's ancestry has been traced far back. The discovery of human bones and implements intermingled with the remains of animals long extinct proved a human habitation in France (Abbeville); Germany (Neanderthal: Fuhlrott 1857); and England (Piltdown: Woodward 1913) during Pleistocene time, and in Java (Do Bois 1891) at perhaps an even earlier date.

The Geologic Time Scale

Since the beginnings of field observations it has been known that many rocks are arranged in layers and that in many places strata of

different colors and texture and composition are piled one upon another in a regular series. But nearly 18 centuries elapsed before it was realized that the stratified rocks contain within themselves the evidences of their origin and reveal a record of alternating lands and seas, of volcanic outpourings and desert winds, of changing climates and surface forms. A yet longer time was required to grasp the stupendous truth that the history of life on the earth is to be deciphered from the organic remains embedded in the hardened sediments.

The true meaning of chronological sequence, the recognition of the fact that the debris of lower strata has been utilized in building the strata next above, was first made clear by Arduino (1713-1795) who separated the rocks of Northern Italy into Primitive, Secondary, Tertiary, and Volcanic (1759). The field methods and manner of presentation developed by Arduino are not unlike those employed today and entitle this pioneer worker to a prominent place among stratigraphers.

An advance is shown in the work of Füchsel (1722-1773)[44] who analyzed the sedimentary masses of Thuringia. By his painstaking field mapping, his insistence that groups of strata have definite chronologic value, and especially by his clear distinction of stratum (Schicht) and formation (*Series montana*), were laid the foundations of stratigraphic geology in Germany.

The high priest of stratigraphy for the eighteenth century was Abraham Gottlob Werner (1749-1817), professor in the School of Mines of Freiberg—the first geologist to obtain world-wide prominence. Werner's contributions to literature are of small importance; his strength lay in his familiarity with the geological researches of his time and even more in his remarkable ability in teaching which made of Freiberg the Mecca for European students. Based on the conception of universal formations as developed by Füchsel, and on the systematic arrangement of minerals as outlined by the Swedish mineralogist, Tobern Bergman,[45] Werner erected the study of rock formations into an independent branch of geology. The essence of his teaching lies in the view that all rock formations are world-wide and that all are chemical precipitates; that the world is like an onion to which successive layers have been added. He conceived of a primeval ocean completely enveloping the earth. From this shell of water were precipitated first the granites and associated green stones, hornblende schists and porphyries, then slates and greywackes, followed in turn by limestone, coal, basalt, and ores; by sand, clay, soapstone, and finally by volcanic ash, some lavas, and jasper. Obviously, all igneous

[44]Füchsel, G. C., Historia terræ et maris ex historia Thuringiæ permontium descriptionem erecta (*Acta Acad. elect. Moguntinae*), 1762.

———, Entwurf zur ältesten Erd und Menschen Geschichte, 1773.

[45]Bergman, Tobern, Physical description of the globe, 1766.

and metamorphic rocks found place with the sediments for there was no place in this scheme for igneous activity, nor for structural changes in the earth's crust. To Werner volcanoes were "burning mountains" —the evidence of spontaneous combustion of buried beds of coal precipitated by an ancient sea. To him the world is the handiwork of Neptune; Pluto was disregarded. In spite of fundamental errors Werner's teachings were dominant to the close of the eighteenth century, and in the early nineteenth century had the backing of leading scholars of Europe, and guided the work of Maclure, Eaton and Silliman, the first American geologists. Only after a contest lasting for two decades did the opponents of the Wernerian School succeed in establishing the difference between igneous masses and sedimentary rocks in the geological series.

This prolonged discussion greatly stimulated observation and encouraged attempts at subdivision of stratified rocks which, however, showed little improvement over the work of Arduino and Füchsel. Progress depended on the development of new methods. The man and the method appeared in an unexpected place. William Smith, a civil engineer (1769-1838), had been quietly at work in all parts of England noting the position, extent, and composition of sedimentary rocks, collecting fossils from each stratum, and recording his observations on colored geological maps and sections. As part of his daily routine Smith noted that certain fossils reappear in the same beds at different localities and that each fossil species is entombed in a definite formation. From this he drew the obvious inference that sedimentary formations may be recognized by their fossil content, and showed that one succession of sediments extends across England from south to east. In this matter-of-fact way the sure foundations of modern stratigraphy were laid; a modest lover of nature had found the way to read the history of the earth—one of the truly great contributions to science. Before William Smith, stratigraphic position and geologic age were based on chemical and mineralogical composition and attitude of rocks; fossils were incidental. Since his day fossils are the final court of appeal for questions of time and order of succession, and correlation of widely separated beds. The adequacy of Smith's methods was amply demonstrated in Conybeare and Phillips' "Outlines of the Geology of England and Wales" (1822)[46] and with the wide distribution of Lyell's famous "Principles of Geology" (1830-1833) came universal recognition of the fact that fossils provided the surest means for comparative study of sedimentary rocks.

Primitive, Transition, Secondary, Tertiary—the recognized subdivisions of the first quarter of the nineteenth century—gradually gave

[46]Conybeare and Phillips' "Outlines of the geology of England and Wales" was the first widely used treatise in the English language.

way to the ages and systems of the modern time-scale. In 1830 the three divisions of the Tertiary based on relative percentage of existing species were established by Deshayes after a comparative study of the Tertiary rocks of England, France, Belgium, Poland, Hungary, and Italy. Lyell (1833) gave them the names now in use: Eocene, Miocene, Pliocene, and later added the term Pleistocene for the most recent alluvium and for the deposits now classed as glacial drift. The equivalents of certain English formations described by Smith were recognized in the Jura Mountains and in 1829 given the name Jurassic. With the addition of Triassic in 1834, the earlier "Secondary Class" became Triassic, Jurassic, and Cretaceous periods of Mesozoic (medieval) time. The analyses of the "Transition Class" of Werner and his contemporaries began with setting limits to the Carboniferous (1821) and continued through the establishment by English workers of the Cambrian (1833), the Silurian (1835), the Devonian (1839), and the Permian (1841) as periods of Palaeozoic time. Even the "Primitive or Primary Class," supposed by the earlier stratigraphers to be the veritable bed-rock of the earth, was resolved by Logan into Huronian (1852) and Laurentian (1853) systems as periods of Archaean (Pre-Cambrian) time. It thus appears that during the forty years following the publication of Smith's geological memoir, English geologists had developed a time-scale by which the relative age of all the sedimentary and igneous rocks of the world could be measured.

Stratigraphic research during the second half of the nineteenth century has added volumes to the history of the earth. The increase in the number of gathered fossils from thousands to tens of thousands permits closer discrimination of horizons and with added knowledge of the breaks in the sedimentary record has led to a recognition of subdivisions in the Silurian, Carboniferous, and Cretaceous. By far the greatest contributions during the past half century came from America. Through state and federal surveys,[47] and university activities, the condition of the earth during Cretaceous, Triassic, and Carboniferous times has been written into the record, and the work of James Hall[48] and his associates has made the stratified rocks of New York State the standard Paleozoic section for the world. American stratigraphers like American paleontologists have advanced from learners to teachers.

During the past quarter century attention has been directed to determining the physical conditions surrounding the deposition of sediments with a view to picturing more clearly the distribution of seas and lands, of streams and mountains, and separating areas of erosion from regions of deposition. The history of climates is also receiving atten-

[47]Government geological surveys: A century of science in America, pp. 193-216, Yale University Press, 1918.

[48]Zittel, Karl von, History of geology and paleontology, p. 442, 1901.

tion and one of the most striking results of modern methods is the proof of glacial conditions not only in the Pleistocene but in the Permian of India, Africa, Brazil, Australia, and Massachusetts, and even among the oldest rocks of China, Norway, and Canada.

It is thus seen that fossils in a modern sense are more than proofs of evolution and more than markers which indicate relative age. They aid in writing the physical geography of the time in which they flourished.

If the record were complete enough it should be possible to locate the seas and lands, the lakes and rivers, reconstruct the mountains and plains, and restore the inhabitants of each geological period. Even with the meager fossil record, geologists are drawing coast lines of the earliest lands, pointing out deserts where rainfall is now abundant and marking ancient tropical seas where cold winters now prevail. One of the most promising developments of the twentieth century is the preparation of physical geographies of important geological eras under the joint authorship of stratigraphers, paleontologists and physiographers.[49]

Age of Earth

The attractive myths of earth origin formulated by most uncivilized races wisely refrain from giving quantitative values to the expression "long ago." The philosophers of India regarded the earth as eternal; the Chaldeans set 2,150,000 years as the age of the earth; Zoroaster was satisfied with 12,000 years, and with the establishment of Christianity in Europe, the Hebrew chronology prevailed and the limiting dates of earth history rested firmly on the recorded teachings of Moses. The views of the Christian world well into the nineteenth century were fairly represented by Bishop Ussher who in 1650 fixed the date of the creation of the earth at 4004 B. C. Strangely enough this figure founded on no facts and no arguments rose to the dignity of a doctrine. For 200 years it appeared on the margin of our English Bibles and was the test of orthodoxy. Even today this date or the corresponding Byzantine date 5509 B. C. is accepted by half of the Christian world. Under the influence of these ideas geologists up to the beginning of the nineteenth century felt compelled to squeeze all geological history into six or seven thousand years. This severe restriction could be harmonized with the growing body of geological fact only by the formulation of extraordinary hypotheses, a state of affairs that led to the magnification of Noah's flood and similar catastrophes as the all powerful agents in molding the surface of the earth.

The scientific world was released from this thraldom by the bold teachings of Hutton that the present slow rate of geological processes must have been the rule since the dawn of geologic history. No wonder

[49]Schuchert, Charles, The progress of historical geology in North America: A century of science in America, pp. 60-121, Yale University Press, 1918.

that this view encountered opposition; it appeared to shake the very foundations of Christianity. The adherents to the established Church chronology had scarcely recovered their breath when Darwin's "Origin of Species" brought from the biological realm data in support of the physical evidence developed by Hutton, Lyell, and others. The theory of evolution obviously demanded enormous drafts on time and was utterly inconsistent with previously accepted views. By the third quarter of the nineteenth century the conclusions of geologists and paleontologists had become too well grounded to permit of substantial modification, but happily the first three words of the Bible, "In the beginning," and the "days" of creation were subject to new interpretations and the smoke of battle cleared away.

During the last half of the nineteenth century the advocates of a very ancient earth found themselves out of accord with the teachings of physics. Under the leadership of Lord Kelvin, mathematical proof was presented that the sun could not have been giving out heat for more than 100,000,000 years, perhaps only 40,000,000, and since the sun must have been producing heat for untold millions of years before life could have existed on the earth, only 10,000,000 to 20,000,000 years could be allowed for geological history. This amount of time is altogether too short for known geologic processes and for the evolution of living forms. When it is realized that the Cretaceous period alone may have had a duration equal to that allowed by Kelvin for all geologic time, the inadequacy of the physical estimates is apparent.

Though viewed with suspicion, the physical evidence appeared for a time irrefutable. Darwin was led to abandon his figures and some geologists undertook to speed up geological processes. In 1895 a re-examination of the physical data by Professor Perry revealed the weakness of Kelvin's arguments and modern students of radio-activity give the geologists not only the one or two hundred millions of years for which they have been contending, but allow 185,000,000 years since Carboniferous time and more than a billion years since the earth's first rocks were formed.[50]

The history of the earth as written during the past century is a fascinating story which has profoundly affected the world's thinking. Some chapters are complete, some need revision, many remain to be written. The interior of the earth and half of the surface of the earth await geological exploration; the mechanics of earth movements are not understood; the causes of variation in climate are imperfectly known; and the origin of life on the earth is shrouded in mystery. The chief problems awaiting solution call for assistance from chemistry, physics, biology, and astronomy, and further advance involves sympathetic coöperation.

[50]Holmes, Arthur, Age of the earth, Harper and Brothers, New York, 1912.